Towards a new generation of cryptographic software

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Goal: Strong link between mathematical object and implementation

About 10 years ago. . .

I hope you're well!

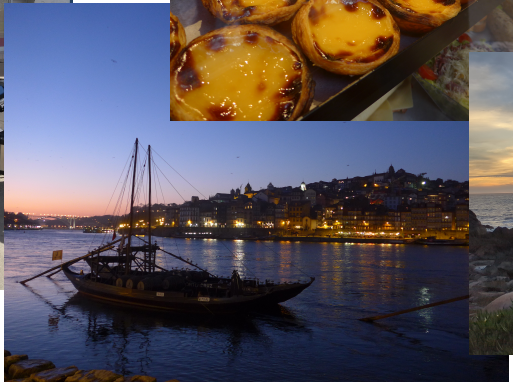
"Gilles Barthe, Ben Laurie, Dan Boneh, Meredith Whittaker, and myself would like to invite you to a workshop on "High Assurance Crypto Software".

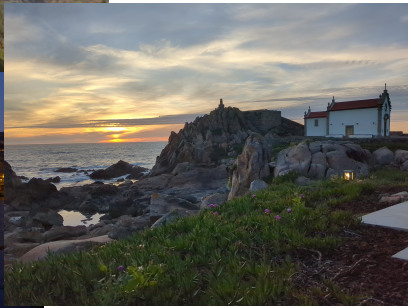
[. . .]

The goal: Bring together the best crypto-implementers and formal-methods verification people from open source, industry, and academia. Introduce them and their projects to each other, and scope and develop practical collaborations that improve verification of crypto code."

—Trevor Perrin, late 2015

Fast forward 4 years (February 2020)





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Goal: Formally verified implementation of Kyber

Almost 6 years later

≈9 papers, 30+ collaborators

Basavesh Ammanaghatta Shivakumar, **Santiago Arranz Olmos**, José Bacelar Almeida, Gustavo Xavier Delerue Marinho Alves, Manuel Barbosa, **Francisca Barros**, Gilles Barthe, Lionel Blatter, Chitchanok Chuengsatiansup, Ignacio Cuevas, François Dupressoir, Luís Esquível, Ruben Gonzalez, **Benjamin Grégoire**, Andreas Hülsing, Vincent Hwang, Jan Jancar, Matthias Kannwischer, **Vincent Laporte**, **Jean-Christophe Léchenet**, Ting-han Lim, Cameron Low, Tiago Oliveira, Hugo Pacheco, Swarn Priya, Miguel Quaresma, Rolfe Schmidt, Antoine Séré, Lucas Tabary-Maujean, Pierre-Yves Strub, Yuval Yarom, Zhiyuan Zhang, **Jieyu Zheng**

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FORMOSA CRYPTO

BOSTON UNIVERSITY

INESCTEC

PQSHIELD

Radboud University

University of BRISTOL

Inria

CASA
CYBER SECURITY IN THE AGE OF LARGE-SCALE ADVERSARIES

ROSENPASS

Universidade do Minho

CRYPTOEXPERTS

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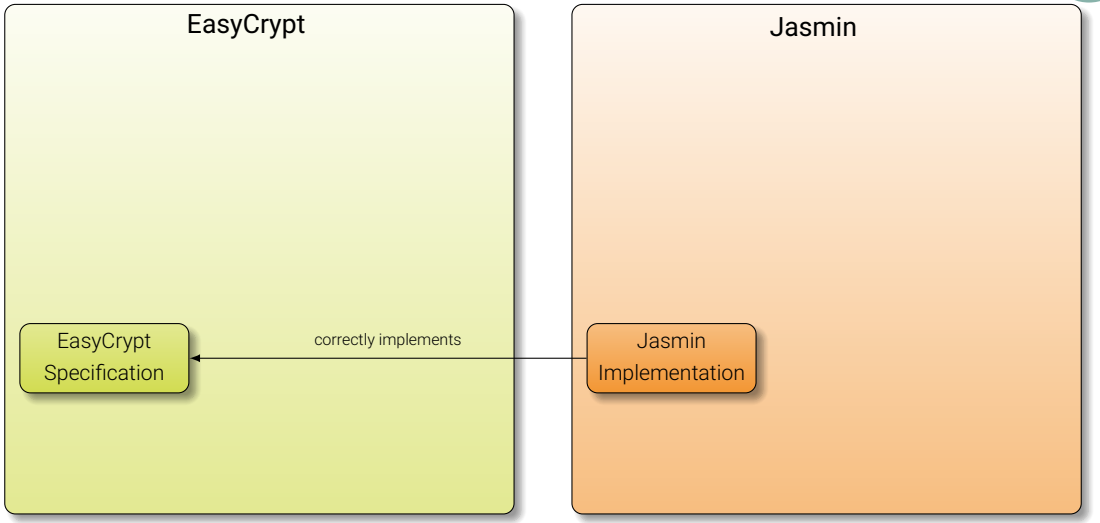
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

PORTO
FACULDADE DE CIÊNCIAS UNIVERSIDADE DO PORTO

UCLouvain

imdea software

My naive view back in 2020



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- Predictable compilation
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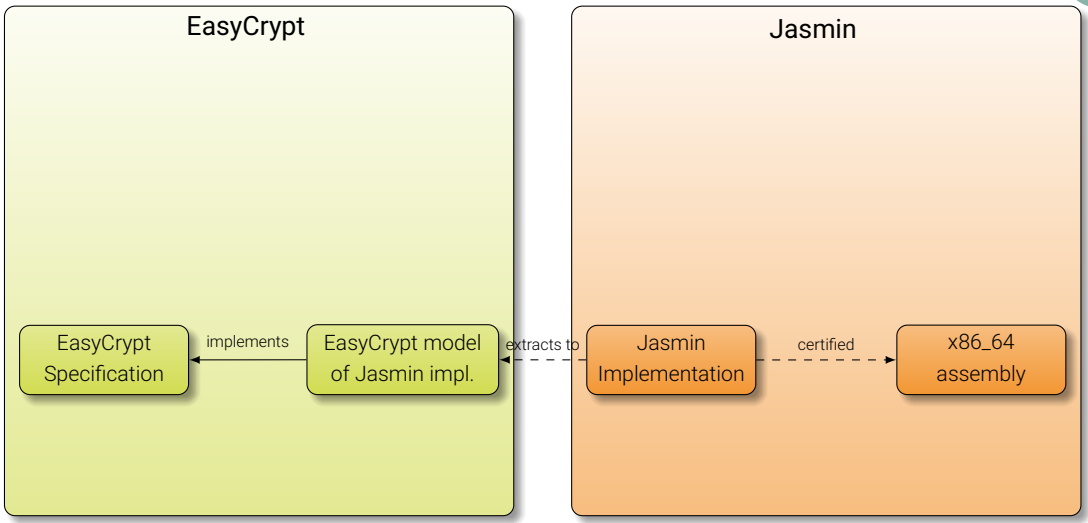
- Register allocation (but no automatic spill-code)
- Important for end-to-end guarantees:
  - *Certified* compilation to assembly (proof in Rocq)
  - Extraction to EasyCrypt
  - Compilation preserves “constant time” (more later)

Refining our high-level view



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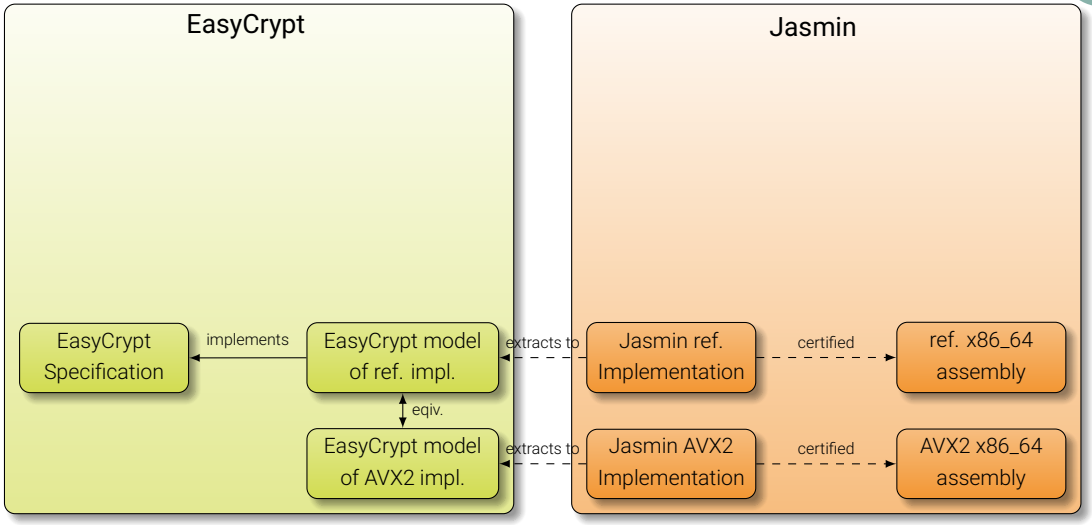

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- Interactive verification framework
- Two languages, one functional, one imperative
- Main purpose: Security reductions, game-hopping proofs
  - Security goals and hardness assumptions as probabilistic programs
  - Support for standard arguments (e.g., hybrid arguments)
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- Additional feature: correctness proofs
  - Relate functional and imperative programs
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- Proofs are manual, but with some automation (e.g., SMT-solver backend)

The specification

- Manuel translation from PDF (Kyber spec, FIPS 203) to EasyCrypt
- Uses both imperative and functional features
- Some interesting tradeoffs, e.g., input/output types for NTT
  - Strong typing: two different isomorphic rings
  - Weaker typing: both just coefficient arrays
  - Weaker typing allows in-place NTT

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  - Weaker typing allows in-place NTT
- Translation and checking could be avoided by **machine-readable standards**

The specification

Algorithm 14 K-PKE.Encrypt($\mathsf{ek}_{\mathsf{PKE}}, m, r$)

Uses the encryption key to encrypt a plaintext message using the randomness r.

Input: encryption key $\mathsf{ek}_{\mathsf{PKE}} \in \mathbb{B}^{384k+32}$.
Input: message $m \in \mathbb{B}^{32}$.
Input: randomness $r \in \mathbb{B}^{32}$.
Output: ciphertext $c \in \mathbb{B}^{32(d_u k + d_v)}$.

$N \leftarrow 0$
$\hat{\mathbf{t}} \leftarrow \mathsf{ByteDecode}_{12}(\mathsf{ek}_{\mathsf{PKE}}[0 : 384k])$
$\rho \leftarrow \mathsf{ek}_{\mathsf{PKE}}[384k : 384k + 32]$
for ($i \leftarrow 0; i < k; i$++)
  for ($j \leftarrow 0; j < k; j$++)
    $\hat{\mathbf{A}}[i, j] \leftarrow \mathsf{SampleNTT}(\rho \| j \| i)$
  end for
end for
for ($i \leftarrow 0; i < k; i$++)
  $\mathbf{y}[i] \leftarrow \mathsf{SamplePolyCBD}_{\eta_1}(\mathsf{PRF}_{\eta_1}(r, N))$
  $N \leftarrow N + 1$
end for
for ($i \leftarrow 0; i < k; i$++)
  $\mathbf{e}_1[i] \leftarrow \mathsf{SamplePolyCBD}_{\eta_2}(\mathsf{PRF}_{\eta_2}(r, N))$
  $N \leftarrow N + 1$
end for
$e_2 \leftarrow \mathsf{SamplePolyCBD}_{\eta_2}(\mathsf{PRF}_{\eta_2}(r, N))$
$\hat{\mathbf{y}} \leftarrow \mathsf{NTT}(\mathbf{y})$
$\mathbf{u} \leftarrow \mathsf{NTT}^{-1}(\hat{\mathbf{A}}^{\top} \circ \hat{\mathbf{y}}) + \mathbf{e}_1$
$\mu \leftarrow \mathsf{Decompress}_1(\mathsf{ByteDecode}_1(m))$
$v \leftarrow \mathsf{NTT}^{-1}(\hat{\mathbf{t}}^{\top} \circ \hat{\mathbf{y}}) + e_2 + \mu$
$c_1 \leftarrow \mathsf{ByteEncode}_{d_u}(\mathsf{Compress}_{d_u}(\mathbf{u}))$
$c_2 \leftarrow \mathsf{ByteEncode}_{d_v}(\mathsf{Compress}_{d_v}(v))$
return $c \leftarrow (c_1 \| c_2)$

```
proc enc_derand(pk : pkey, m : plaintext, r : W8.t Array32.t) : ciphertext = {
  (tv,rho) ← pk;
  _N ← 0;
  thati ← EncDec.decode12_vec(tv);
  that ← ofipolyvec thati;
  i ← 0;
  while (i < kvec) {
    j ← 0;
    while (j < kvec) {
      XOF(O).init(rho,W8.of_int i, W8.of_int j);
      c ← Parse(XOF,O).sample();
      aT[(i,j)] ← c;
      j ← j + 1;
    }
    i ← i + 1;
  }
  i ← 0;
  while (i < kvec) {
    c ← CBD2(PRF).sample(r,_N);
    yv ← set yv i c;
    _N ← _N + 1;
    i ← i + 1;
  }
  i ← 0;
  while (i < kvec) {
    c ← CBD2(PRF).sample(r,_N);
    e1 ← set e1 i c;
    _N ← _N + 1;
    i ← i + 1;
  }
  e2 ← CBD2(PRF).sample(r,_N);
  yhat ← nttv yv;
  u ← invnttv (ntt_mmul aT yhat) + e1;
  mp ← EncDec.decode1(m);
  v ← invntt (ntt_dotp that yhat) + e2 + decompress_poly 1 mp;
  c1 ← EncDec.encode10_vec(compress_polyvec 10 u);
  c2 ← EncDec.encode4(compress_poly 4 v);
  return (c1,c2);
}
```

Mechanizing the security proof

Goal: Link specification to IND-CCA notion

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- Typical game-hopping proof for abstract LWE-based PKE
- Refine to concrete parameters of K-PKE
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Step 3: IND-CCA security of ML-KEM

- Prove IND-CCA for MLKEM_OP
- Central difference: SHA3-512 replaced by RO

Linking the spec to the code

Spec $\leftrightarrow$ ref impl.

- Montgomery and Barrett reductions
- Lazy reductions (bounds checking!)
- "Funny" code, e.g., for `a = a/3329`

```
a *= 80635;
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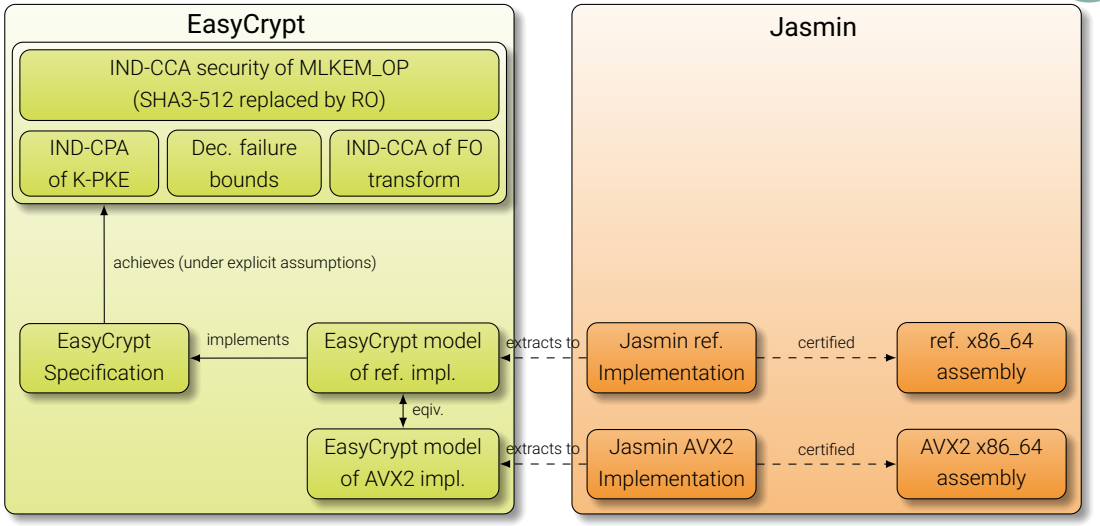
- Massive manual effort with quite some student frustration
- Significant improvement 2025:
  - *automated* circuit-equivalence checking
  - integrated in EasyCrypt, interleave with deductive reasoning
  - faster verification, more robust proofs, easier proof maintenance

So, where are we?



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The new way

- Master's thesis by **Francisca Barros**
- Modular design
- Safety contracts and assertions in Jasmin
- Automatic discharge of assertions
- Prove remaining assertions in EasyCrypt

```
fn _gen_matrix_avx2
( reg mut ptr u16[MLKEM_K * MLKEM_K * MLKEM_N] matrix
, reg const ptr u8[32] rho
, #spill_to_mmx reg u64 transposed
) -> reg ptr u16[MLKEM_K * MLKEM_K * MLKEM_N]
requires {is_arr_init(rho,0,32) && 0<= transposed && transposed <= 1}
ensures  {is_arr_init(result.0,0,MLKEM_K * MLKEM_K * MLKEM_N * 2)}
{
  ...
}
```

Security – “constant time”

- Enforce constant-time on Jasmin source level
- Every piece of data is either `secret` or `public`
- Flow of secret information is traced by type system

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- **Jasmin compiler preserves constant-time!**
- Explicit `#declassify` primitive to move from `secret` to `public`
- `#declassify` creates a proof obligation!

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- Some arithmetic instructions also leak through timing
- Example: `DIV` (exploited in “KyberSlash”, CHES 2025)
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  - Subset of x86_64 instructions **guaranteed** to not leak through timing
  - Requires switching CPU to DOIT mode
- Support for DOIT in Jasmin compiler
  - Use only DOIT instructions on secret inputs
  - No serious limitation for most *optimized* code
  - All relevant vector instructions are DOIT

Spectre v1 (“Speculative bounds-check bypass”)


```
stack u8[10] public;
stack u8[32] secret;
reg u8 t;
reg u64 r, i;

i = 0;
while(i < 10) {
  t = public[(int) i] ;
  r = leak(t);
  ...
}
```

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- Idea: maintain misprediction predicate `ms` (in a register)
- At every branch use arithmetic to update predicate
- Option 1: Mask every loaded value with `ms`
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- Option 1: Mask every loaded value with `ms`
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- Effect: during misspeculation “leak” constant value
- Implemented in LLVM since version 8
  - Still large performance overhead
  - No formal guarantees of security

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- No need to mask loads into registers that never enter leaking instructions
- `secret` registers never enter leaking instructions!
- Obvious idea: mask only loads into `public` registers

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  - `#declassify` requires cryptographic proof/argument
- Still: allow branches and indexing only for `public`
- Also, allow non-DOIT instructions only on `public` inputs

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- No cost if those inputs don't flow into leaking instructions
- Even better: Spills don't need `protect` if there is no branch between store and load
- Even better: "Spill" public data to MMX registers instead of stack

If there's a Spectre v1...

- Spectre v2: indirect branches (not supported by Jasmin)
- Spectre v3, aka "Meltdown": fix in HW and firmware
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- **Spectre-RSB**: function return speculates *anywhere*
- Attacker can choose to speculate right behind any defense!
- Solution in Jasmin:
  - Rewrite all returns through "branch table"
  - Implement branch table through *conditional* branches
  - Speculate only to one of the call sites
  - At call sites all **public** values become **transient**
  - Use `#protect` and `ms`

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Scrub all (sensitive) data from memory (stack) and registers when crypto routine returns.

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Failure modes

0. Don't perform any zeroization

Clearing sensitive data

"...A cryptographic module shall provide methods to zeroize all plaintext secret and private cryptographic keys"

—FIPS 140-3, Section 9.7.A

Goal of zeroization

Scrub all (sensitive) data from memory (stack) and registers when crypto routine returns.

Failure modes

0. Don't perform any zeroization
1. Dead-store elimination

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0. Don't perform any zeroization
1. Dead-store elimination
2. Only API-level stack zeroization
3. Don't scrub source-level invisible data
4. Mis-estimate stack space when scrubbing from caller

Clearing sensitive data (ctd.)

Solution in Jasmin compiler

Zeroize used stack space and registers when returning from export function

Clearing sensitive data (ctd.)

Solution in Jasmin compiler

Zeroize used stack space and registers when returning from export function

- Make use of multiple features of Jasmin:
  - Compiler has global view
  - All stack usage is known at compile time
  - Entry/return point is clearly defined

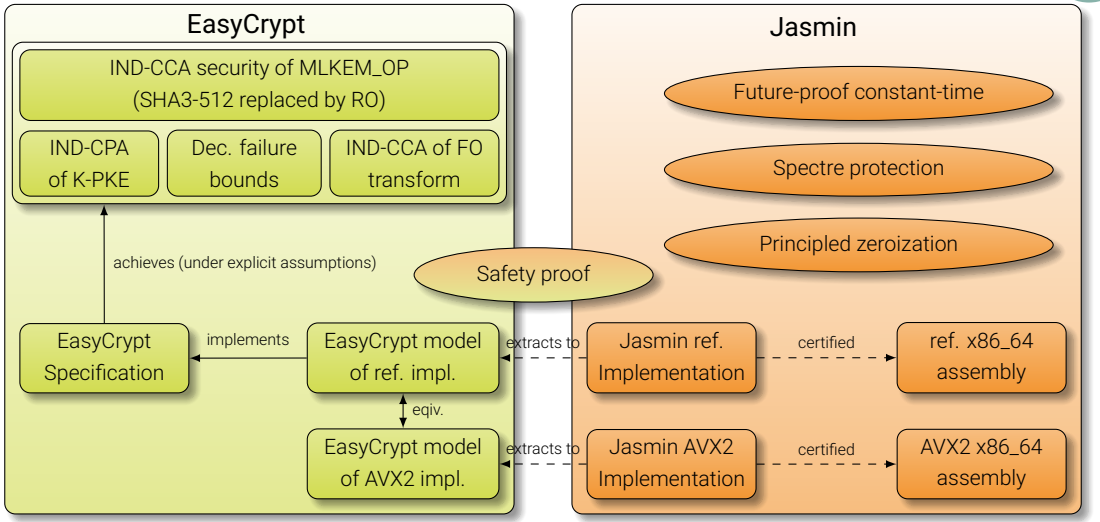
Clearing sensitive data (ctd.)

Solution in Jasmin compiler

Zeroize used stack space and registers when returning from export function

- Make use of multiple features of Jasmin:
  - Compiler has global view
  - All stack usage is known at compile time
  - Entry/return point is clearly defined
- Performance overhead for Kyber768 (on Comet Lake):
  - 0.59% for Keypair
  - 0.24% for Encaps
  - 1.04% for Decaps

The next generation of crypto software



Is it fast?

Cycles for ML-KEM-768

CPU	Implementation	keypair	enc	dec
8700K	Jasmin AVX2*	40134	40599	43437
	pq-crystals	39722	39761	46161
11700K	Jasmin AVX2*	37458	37798	39970
	pq-crystals	36958	38082	42566
13900K	Jasmin AVX2*	34732	35212	43784
	pq-crystals	31448	32090	36064

*with Spectre-v1 (without Spectre-RSB) protections

Stay tuned

Work in progress (selection)

- Deployment in Signal's contact discovery (RWC talk upcoming!)
- Integrate Spectre-RSB protections
- Implement in **crypto agent** process
- Extend to more architectures and more primitives (next up: ML-DSA)
- Interface to super-optimizers (e.g., CryptOpt, SLOTHY)
- Improve usability/scalability of tools

Longer-term plans (selection)

- Guarantee preservation of speculative constant time
- Masked implementations
- Machine-readable standards (?)

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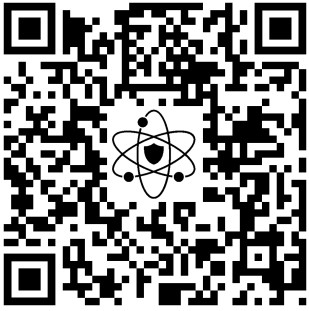
Thank you!



https://github.com/pq-code-package/mlkem-libjade

https://formosa-crypto.org